# Lesson Learned

## Transient Induced Misoperation: Approach I
## (Control Circuit Transient Misoperation of Microprocessor Relay)

**Primary Interest Groups**
Transmission Owners (TOs)
Generator Owners (GOs)
Transmission Operators (TOPs)
Generator Operators (GOPs)

**Problem Statement**
Voltage transients were found to initiate protective relay digital inputs during close-in faults to a hydroelectric dam. The false inputs resulted in multiple powerhouse line protection misoperations and the unnecessarily tripping of hundreds of megawatts of generation. Due to the vintage of the equipment and a failure of the relay to properly log events, little data was initially available for troubleshooting. The powerhouse line relays at both the substation and powerhouse were owned and operated by the TOP but were connected to and powered by the GOP's control circuits and battery at the powerhouse.

**Details**
In 2019, a 230 kV bus fault occurred at the substation where several hydro generators interconnect with the power system. Two separate misoperations of the line protection at the powerhouse caused two powerhouse lines to trip unnecessarily, resulting in a loss of 221 MW. The relay trip was not initiated by an internal protection element; it was externally initiated via a 125 VDC direct transfer trip (DTT) input on the line relay at the powerhouse. The signal lasted less than a power system cycle and sent a direct trip to the remote end (one of the two relays failed to target it).

A 47 kΩ resistor was added in parallel with the DTT input on all line relays at the powerhouse to dampen the perceived fault-induced transient. Subsequent lab testing found the line relay could initiate a direct trip to the remote terminal and not provide LED trip targets if an ac source was connected in parallel with the dc source. A 15 kHz continuous recorder was installed to monitor supply voltage to the relay and the voltage across the DTT input of one of the two misoperating terminals.

In 2020, a similar event from a single phase line fault occurred on a 500 kV line in close proximity to the powerhouse. The fault resulted in a misoperation of the same two powerhouse lines causing 315 MW of hydro generation to be tripped. The 15 kHz continuous recorder captured a brief full positive shift of the dc control power with respect to ground. A voltage pulse was seen across the DTT input of the monitored relay followed by a 60Hz AC voltage component lasting the same duration as the transmission line fault (approximately 2.5 cycles); see **Figure 1** and **Figure 2**. The transient ac signal was comparable to the previously conducted lab tests that showed an ac signal was capable of initiating the relay input without the DTT LED trip target. The conditions that the relay is expected to operate at (above 70 V for 4 ms) occurred too briefly in the 2020 event. Unfortunately, the transmitting relay did not log an event, and the receiving relay that did trigger an event masked the actual duration with a time delay dropout of the trip signal (e.g. "min trip duration").

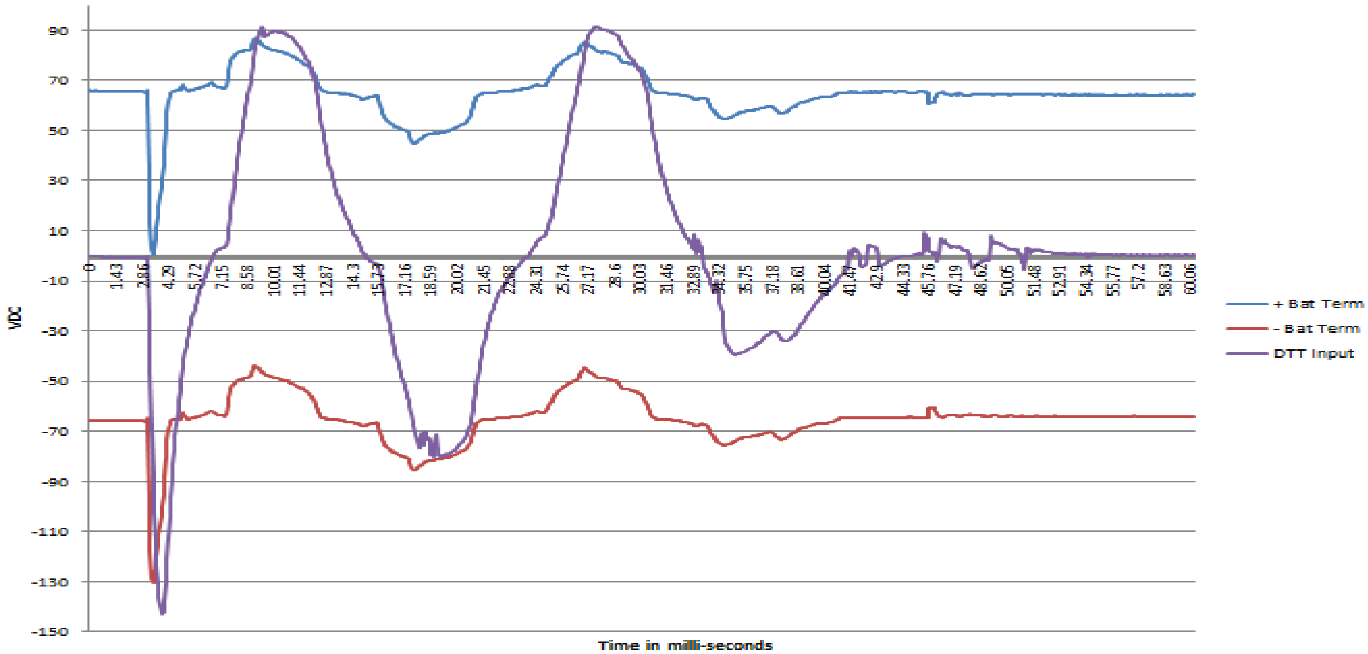


**Figure 1: 15 kHz continuous recorder data measuring relay supply voltage (Blue and Red) and the DTT input voltage across the installed resistor (Purple)**

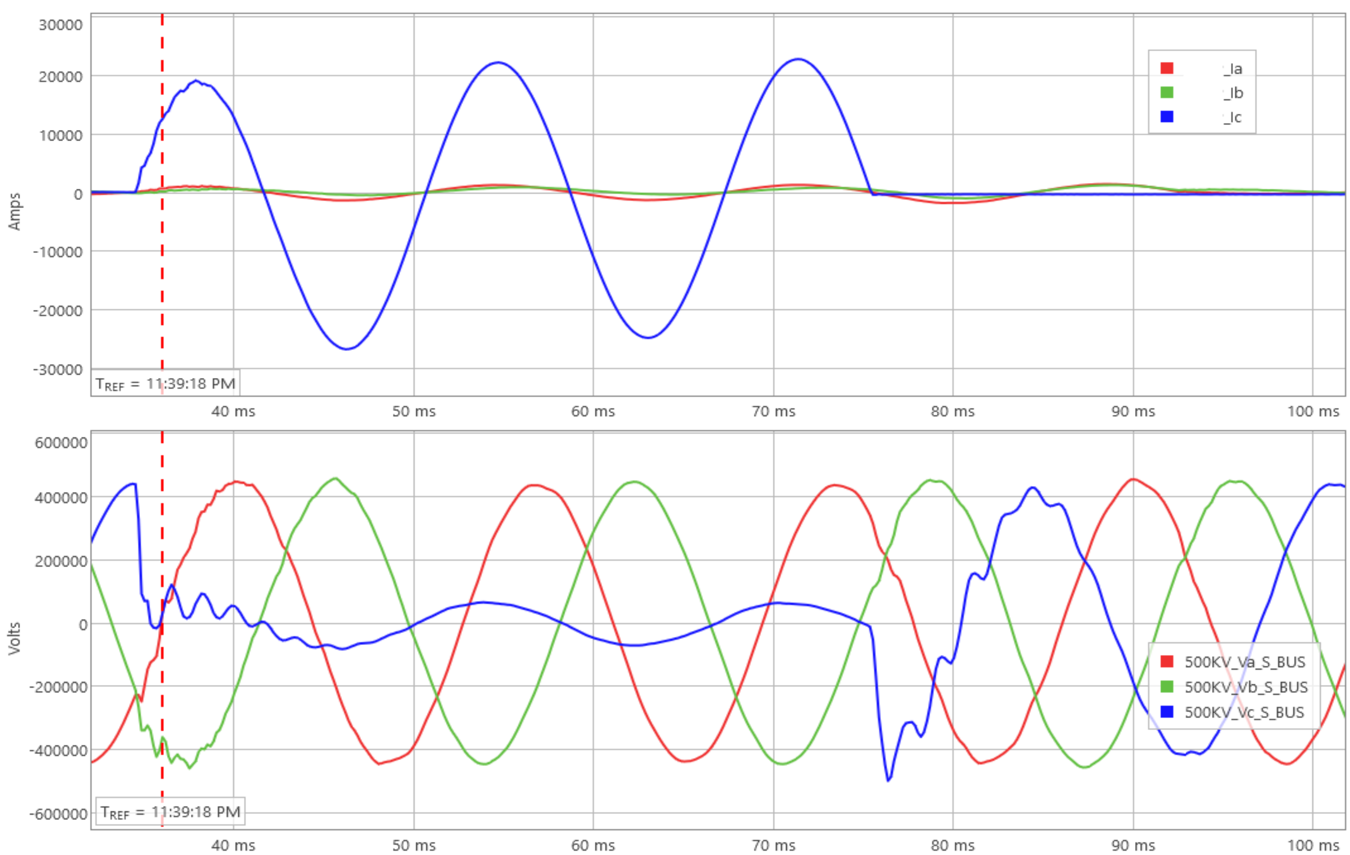


**Figure 2: Event from digital fault recorder, located at the substation adjacent to the powerhouse, showing line current (top) and bus voltage (bottom) during the 2020 500 kV line fault.**

The generator step-up (GSU) transformers at the powerhouse rely on the line breaker at the substation to clear for transformer faults (see **Figure 3**). The powerhouse line relay DTT input is used to transmit operator control and transformer protection trips to the substation. The two powerhouse lines with a history of misoperation have two GSUs per line relay and consequently more control cabling than a line with only one GSU (GSU transformer relays misoperated in 2017 for a similar close in fault). The remaining four lines that had only one GSU per line have not misoperated.

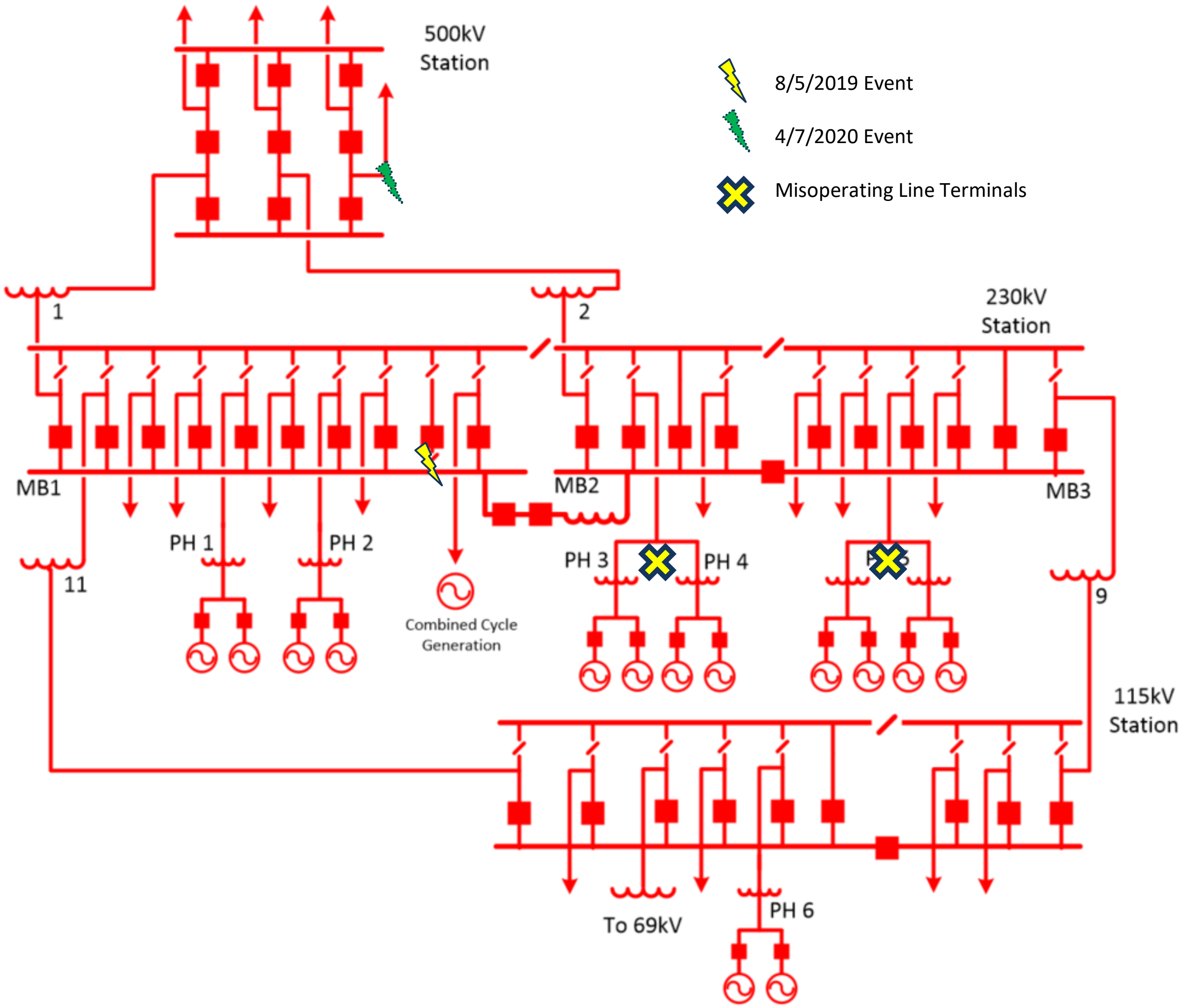


**Figure 3: One line diagram of the impacted station.**
**Line relay misoperations occurred on powerhouse lines 3/4 and 5.**

## Corrective Actions

A review of the location history found that the powerhouse line relays were upgraded around 1998 (pilot wire schemes were used previously). The issues did not begin until after the addition of a second 1,300 MVA 500/230/34.5 kV autotransformer with delta tertiary (ground source) at the substation in 2016. Installation of the autotransformer increased the ground fault current and subsequently the magnitude of the ac transient seen in the controls. The root cause of the voltage transients on the line relay's DTT input is believed to be the result of high ground current present at the powerhouse during high magnitude ground faults.

Several fixes were developed between the TOP and GOP to prevent further Misoperations, listed here:

- The pull down resistors originally installed were a standard size used for other input sensitivity mitigation applications. Monitoring equipment provided visibility of the transient voltages during the high magnitude faults during which the powerhouse contributed significant fault current. Event information, in-lab testing results, and a review of manufacturer literature resulted in a change to a potentially more effective 23 kOhm resistor. To provide context to resistor sizing, a 125 VDC repeat relay coil is approximately 9 kOhm.
- The long cable that carried the control room trip back to the line protection sat in the same cable tray as the unshielded current transformer (CT) cable for the control room board meter (see **Figure 4**). It was theorized that the large current flowing through the CT cable during a close-in fault could have been the cause of the DTT transient in conjunction with improper CT grounding. CT grounds were checked, and secondary injection testing was performed in an attempt to rule out coupling between the CT and DTT control circuit during faults. A 100A AC signal designed to look like a single-line-to-ground fault was simulated into the board meter CT circuit while monitoring the DTT input of the associated line relay. CTs were found to be properly grounded and no corresponding transient was measured during secondary injection.
- Although not a player in these events, the lockout is recognized as a single point of protection failure that the entity plans to address.

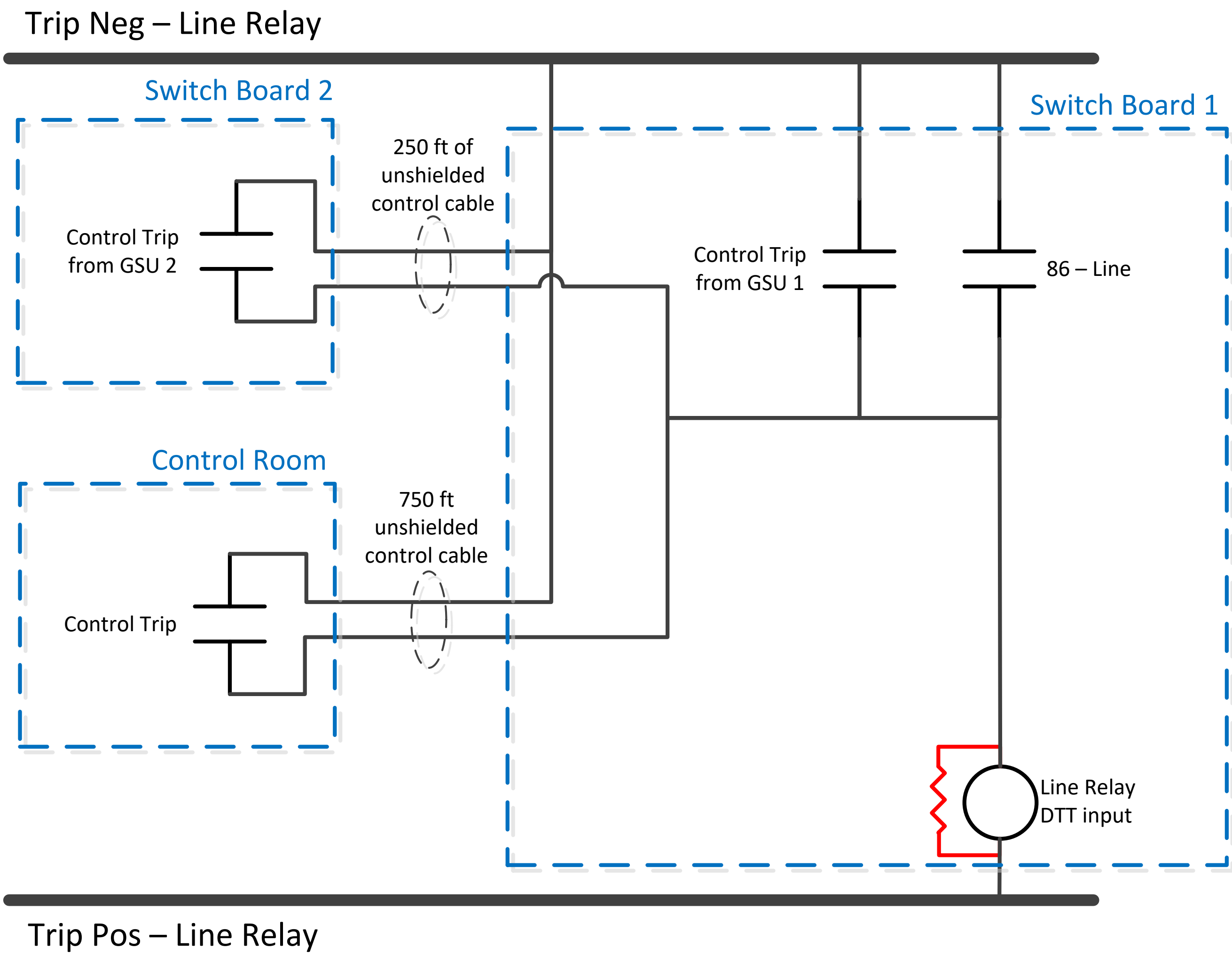


**Figure 4: Original DTT circuit for two GSU Transformer per line protection package. Single GSU lines do not have a Control Trip from GSU 2.**

- The control handle trip circuits run for several hundred feet from the protection cabinet to the control room at the powerhouse. The length of the cable resulted in higher cable capacitance and an increased likelihood of ac coupling during high magnitude ground faults. The GOP rewired the control trip circuits to terminate into the GSU protection, a more advanced microprocessor relay. The redesign of the circuit allowed for the implementation of a 100 ms (6 cycle) delay of the control trip signal for transient ride through during normal clearing faults. A longer delay has been requested by the TOP to ride through potential stuck-breaker fault events.

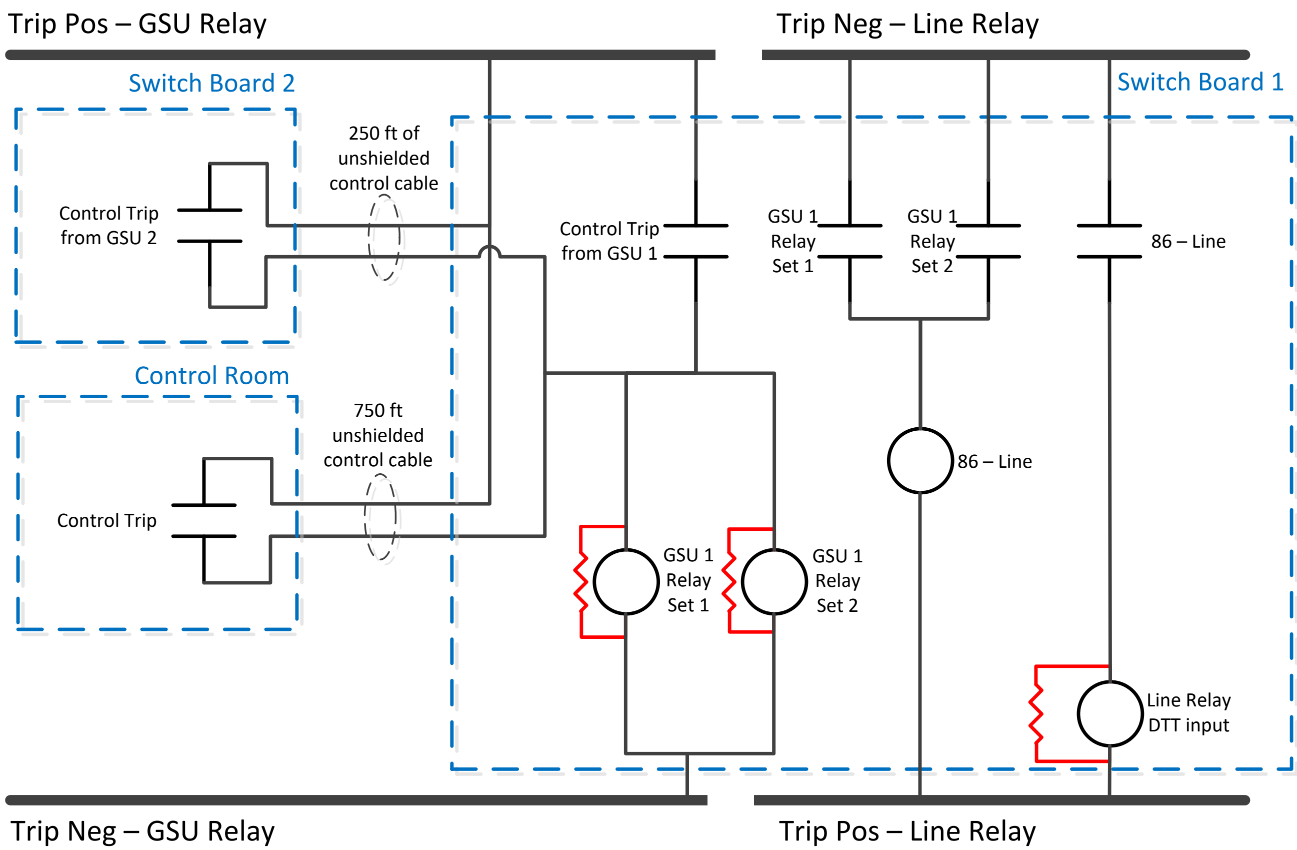


**Figure 5: Modified protection and control trip circuit used to trip substation breaker. Both Set 1 and 2 GSU relays trip 86-line lockout relay.**

- Relay-to-relay communication will be installed from the GSU protection to an alternate powerhouse line relay at the substation if another misoperation occurs. By using a relay-to-relay communication channel from the GSU protection to the alternate line relay at the substation, all DTT functionality can be moved to a more secure system. The TOP and GOP are waiting for future high magnitude faults to provide assurance that completed mitigation efforts will prevent further misoperation.
- The powerhouse line protection will be replaced in the near future with more sophisticated microprocessor relays with the DTT circuit divided across multiple inputs (control and protection) on the new line relays. The electrically smaller protection signal of the DTT circuit can be passed through to the substation with no intentional delay to maintain fast clearing times for GSU faults. The electrically larger control signal of the DTT circuit will be time delayed for transient ride through. Additionally, the new design will address the single point of protection failure vulnerability that the 86-line lockout represents in the present design (see **Figure 5**).
- A powerhouse control and cabling project is planned to remove and replace unshielded cabling with shielded. Shielding should increase the DTT circuit noise immunity.

Later in 2020, a thunderstorm resulted in multiple faults in the vicinity of the powerhouse. A 115 kV PH line fault was observed during this storm (see **Figure 6**). The fault was smaller in magnitude than the 500 kV single phase fault observed during the earlier 2020 misoperation, but a transient was observed and the relays did not false trip. At that time, the only corrective action fully implemented was the updated resistor sizing on the DTT input. While more events will need to occur to verify the success of the corrective actions, this was a positive indication of the effectiveness of the corrective actions.

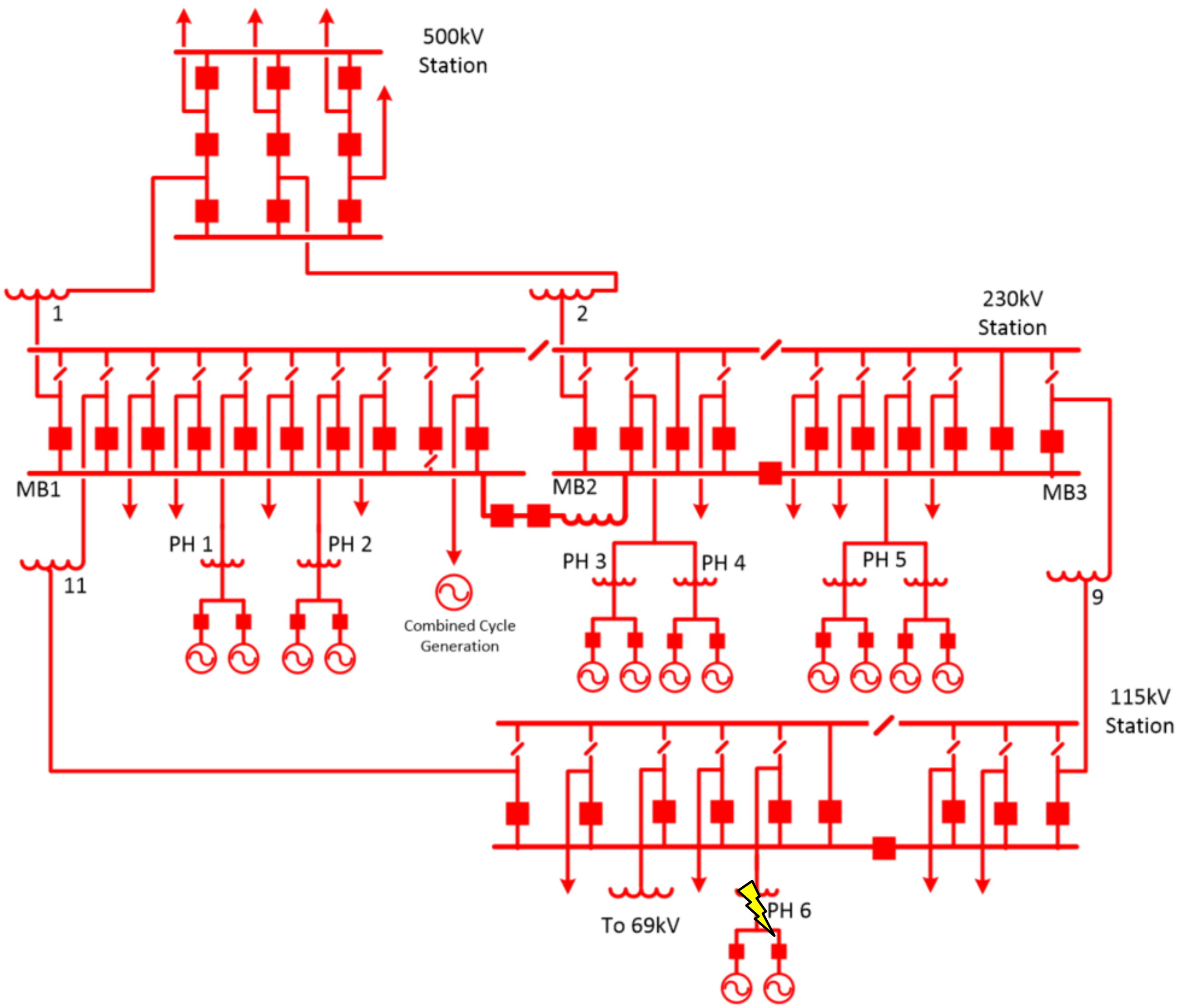


**Figure 6: One-line diagram of substation showing the 115 kV Bus and powerhouse line impacted by the later 2020 close-in fault**

## Lesson Learned

- Troubleshooting the transient-induced relay misoperation was a challenge due to the initiation method of the misoperation and lack of visibility. The misoperation only triggered in the field via a close-in fault to the powerhouse, making the misoperation impossible to manually replicate. Following the event in 2019, resistors were added to the DTT inputs and monitoring equipment was installed to provide event data during the next close-in fault. Only by acting quickly to implement these corrective actions was it possible to capture data for the 2020 event. While the actions taken following the 2019 event did not prevent the 2020 misoperation, they did provide the insight necessary to develop the next iteration of corrective actions. By implementing fixes based on available information and adding tools for better visibility of the issue, it is possible to take an iterative approach to correcting sporadic issues on the power system that may be difficult or impossible to manually replicate.

- Transient-induced relay misoperations are prime examples of the types of issues that can arise when various generations of equipment and designs are combined together at a single site. The original installation of the powerhouse line protection and control circuits utilized unshielded cables in the same cable tray to save money and space. The original electromechanical design experienced no significant issues for years. Electromechanical devices inherently have a higher tolerance for electrical noise due to the increased input burden and slower operation. After replacing the electromechanical devices with an early vintage of microprocessor relay (lower input burden and faster operate time), the circuit's noise immunity diminished. Additionally, the design utilized a single input for both the control and protection trips, increasing the amount of cabling connected to the relay input. The additional cabling made the circuit more susceptible to ac transient coupling (electrostatic and/or electromagnetic induction) during the high ground fault current that is characteristic of close-in faults near generation facilities.
- It is prudent to reduce the amount of cabling connected to a single input and increase the burden of the microprocessor relay input. One method to increase the input burden is to install a parallel resistor.
- To mitigate issues associated with cable installations, cabling connected to an input can be reduced by separating functions into separate inputs or migrating to digital controls. For example, control trips do not require the same speed as a protection action and should instead be placed on a separate input with a short time delay to reduce the likelihood of transient-induced misoperation. Circuit separation has the added effect of decreasing both the capacitance of the circuit and the potential of ac coupling.
- To secure the scheme during both normal protection trips and postulated close in faults with a stuck breaker event, extending control trip time delays can be employed.
- When adding equipment that may significantly increase the ground fault current, evaluate the potential change in the magnitude of the ac transients seen by the controls.
- In some cases, cabling issues require additional care during the design of relay replacements. When mixing microprocessor relays with legacy coil relays, inputs may differ greatly between them and electrically noisy environments might not be tolerated. Circuits may need to be broken up to reduce the amount of capacitance and/or coupling.
- Always evaluate the system for these factors when installing new relays.

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